CRACK DETECTION IN FUSELAGE PANELS BY A NARROW-BAND LASER-BASED ULTRASONIC SYSTEM

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INTRODUCTION

Surface acoustic waves can be used for the characterization of mechanical properties of materials, as well as to investigate the near-surface region of a solid for cracks and other flaws by probing for the presence of scattering sources. In the non-destructive characterization of solids, laser generation of ultrasound as well as interferometric detection of the surface waves are particularly attractive in view of the non-contacting nature of such systems. In recent studies, accurate detection of surface wave speed and attenuation have been shown to be possible by the use of dual-probe laser interferometers[1,2]. A number of authors have also shown the feasibility of generating ultrasound through the use of high-power lasers that generate acoustic waves either by thermoelastically heating the solid, or by ablating the material. For nondestructive applications, however, it is undesirable to ablate the material, and hence one must confine laser generation to the thermoelastic regime. However, in view of the relatively low sensitivity of typical optical detection systems, the generated surface waves have to be sufficiently strong and can be obtained only in the ablation regime if a *single* laser source is used. Therefore, a number of schemes have been proposed in recent years that involve the addition of an ensemble of acoustic waves generated in the thermoelastic regime from distributed or discrete-array sources. While the acoustic signal generated from each of the illumination regions in the array might be relatively weak, by appropriate spacing of the illuminated regions, the signal at the detection point can be made substantially stronger than the noise, thereby enabling enhanced laser interferometric detection. Techniques that use this principle include generation of a converging surface wave by laser illumination of an annular region[3], and continuous excitation of a surface wave with a scanning laser beam which follows the propagating wave[4].

The generation of acoustic waves using an array of illumination regions also lends itself to an improved signal-to-noise ratio of the system. The signal-to-noise ratio for a shot noise (white noise) limited optical detection system can be shown to be as[5]

$$\mathrm{SNR} = \frac{\text{signal power}}{\text{noise power}} \propto \frac{p}{\Delta F} \tag{1}$$

where p is the energy of the signal, and ΔF is the bandwidth of the detection system. Therefore, an increase of generated ultrasound signal amplitude in a specified narrow-band

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

and an appropriate reduction of the detection bandwidth corresponding to the narrow-band will improve the signal-to-noise ratio, and hence the sensitivity of the laser ultrasonics system. While generation from a single short laser pulse typically leads to broadband acoustic signals, an array of sources can be phased appropriately to obtain strong narrow-band signals.

A number of schemes have been proposed for generating narrow-band acoustic signals. These include using illumination through periodic surface masks[6], interference of two intersecting laser beams[7], repetitive illumination by a lenticular array[5], and optical-fiber-guided laser arrays[8]. The use of surface masks or lenticular arrays, however, will lead to non-uniform line sources in the array, with the central lines always being stronger than the outer lines due to the Gaussian spatial intensity distribution of the laser beam in the TEM_{00} mode. Also, as previously noted, for interferometric detection the acoustic waves must be sufficiently strong, requiring that the generation be ideally just below the ablation range (and not any stronger so as to prevent damage to the illuminated surface). If optical fibers are used to create the array, the high laser power required is likely to damage them. For these reasons, an alternate approach is described in this work where narrow-band surface waves are generated by a line-array of laser pulses formed using cylindrical lenses and a holographic diffraction grating[9]. Damage to the grating can be prevented by simply passing an expanded laser beam through the grating prior to focusing the beam on to the test specimen. The proposed setup is very flexible allowing for optimum generation of narrow-band acoustic waves, and providing easy adjustment of the center frequency and bandwidth of the generated surface waves.

PRINCIPLE OF NARROW-BAND SIGNAL GENERATION

For laser generation of ultrasound in the thermoelastic regime, the heat absorption takes place within a very thin layer on the surface. When the thickness of the layer is much smaller than the wavelength of the ultrasound, which applies to the experiments discussed in this paper, the surface acoustic wave basically depends upon the spatial and temporal profile of the laser beam. For generation by a very short laser pulse in the TEM_{00} mode, the temporal profile can be regarded as a delta function, and the spatial profile is a Gaussian distribution. For a single line-focused beam, neglecting the variation along the length of the line while assuming a Gaussian intensity distribution across its width, the generated plane surface wave can be shown to be approximately proportional to[10],

$$h(t) \propto (x-ct)e^{-4(x-ct)^2/d^2} \tag{2}$$

where x is the propagation distance, c is the surface wave speed and d is the characteristic width of the Gaussian distribution, defined as the width where the intensity drops to $1/e$ of the maximum value. Application of the Fourier Transform on $h(t)$ gives the amplitude spectrum of the single line generated surface wave as:

$$H(f) \propto f e^{-\pi^2 f^2 d^2/4c^2} \tag{3}$$

The signal generated by an *array* of N equally spaced identical line sources (line-array) can then be written as

$$g(t) = \sum_{n=1}^{N} h(t-n\Delta t) \tag{4}$$

where Δt is the surface wave propagation time between two adjacent line sources. The frequency spectrum of $g(t)$ is then given by:

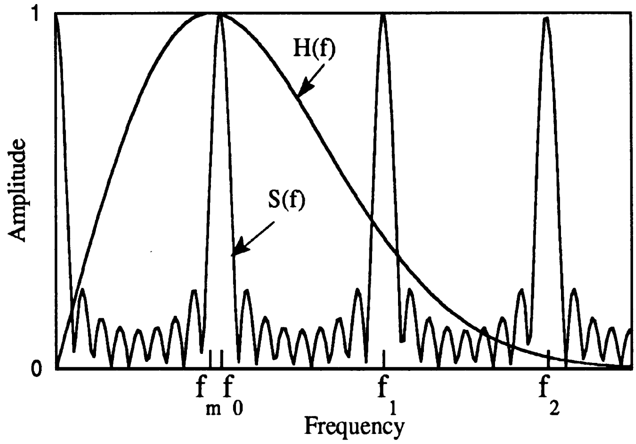

Fig. 1 Theoretical spectra $H(f)$ and $S(f)$.

$$G(f) = NH(f)S(f) \tag{5}$$

where $S(f)$ is an array function defined as:

$$S(f) = \frac{\sin(\pi N f \Delta t)}{N \sin(\pi f \Delta t)} \tag{6}$$

Typical theoretical $H(f)$ and $S(f)$ spectra are plotted in fig. 1 for a value of $N=9$ which is applicable to the current experiments. It can be noted that $H(f)$ is a wide-band spectrum with a maximum amplitude occurring at frequency $f_m=\sqrt{2}c/\pi d$. However, for the array function $S(f)$, there are narrow-band principal peaks appearing at frequencies $f_n=(n+1)f_0$, $n=0,1,2\cdots$, where $f_0=1/\Delta t$ is the fundamental frequency in $S(f)$. The subsidiary peaks of $S(f)$ are much smaller in amplitude when N is large. Defining the bandwidth by the first zeros on both sides of the principal peaks, it can be seen that the signal bandwidth is $2f_0/N$. Therefore, the number of lines N determines the signal bandwidth.

From fig. 1, it is obvious that the optimum condition for a narrow-band signal generation is achieved when f_m coincides with one of the f_n's. Considering that Δt is equal to the line separation distance δ divided by surface wave speed c, the line-array parameters for optimum generation of surface waves at frequency f can be seen to be given by

$$\delta = c/f \text{ and } d = \sqrt{2}\delta/\pi \tag{7}$$

GENERATION OF NARROW-BAND SURFACE ACOUSTIC WAVES

A schematic diagram of the line-array generation is shown in fig. 2. The specimen is an aluminum block of dimensions 11×7×5.5cm with surface wave velocity 2.901mm/μs. A Q-switched Nd:YAG laser is used to excite the surface waves. The laser pulses are of 10 ns

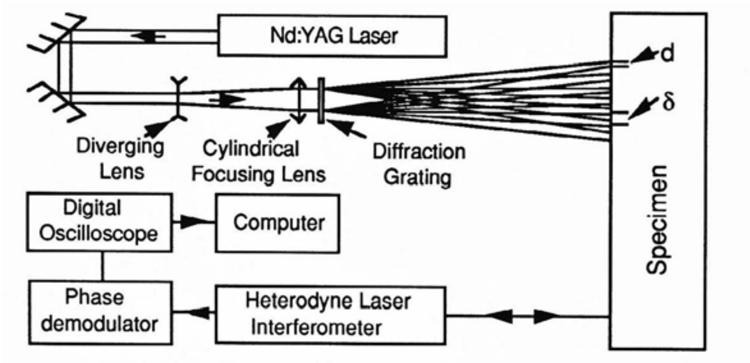

Fig. 2 Schematic of the experiment set-up for narrow-band signal generation.

duration. The Nd:YAG laser beam is first expanded by a convex spherical lens and then focused by a concave cylindrical lens to form a line illumination. An optical binary phase grating is positioned behind the cylindrical lens to diffract the beam into a number of orders of beams propagating at different angles. Note that the width and length of the line are controllable by changing the distances between the specimen and the convex and the concave lenses, respectively. From diffraction theory of optics[11], the m'th order beam propagates at an angle $\theta_m = sin^{-1}(m\lambda/ p) \approx m\lambda/ p$ under the small angle approximation, where $m=0,\pm1,\pm2 \cdots$.

When the spacing and line width are optimized as given by Eq. (7), a tone-burst like surface wave can be generated as shown in fig. 3(a). Figure 3(b) is the spectrum of the signal in fig. 3(a). Also shown in fig.3(b) is the broadband spectrum of the signal generated by the single line of zeroth order from the line-array. For the purpose of verifying the optimum generation condition, the broadband spectrum is smoothed and scaled by an arbitrary constant, and plotted in the figure. The fundamental peak is seen to be aligned with the maximum amplitude of the single line generation in fig. 3(b), showing that optimized generation is achieved. The total power of the narrow-band signal is calculated to be about *9* times that of the wide band signal, and the bandwidth reduction is about *1/9*. Therefore, according to Eq. (1), the signal-to-noise ratio is increased by about *81* times after narrow band-pass filtering.

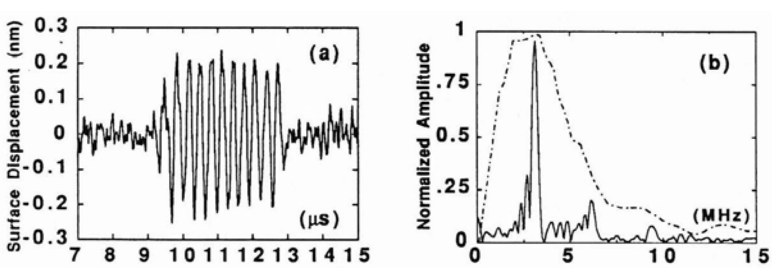

Fig. 3(a) Surface wave tone-burst generated under the optimized condition. (b) The spectrum of the signal in Fig. 3(a), showing the optimum narrow-band signal generation.

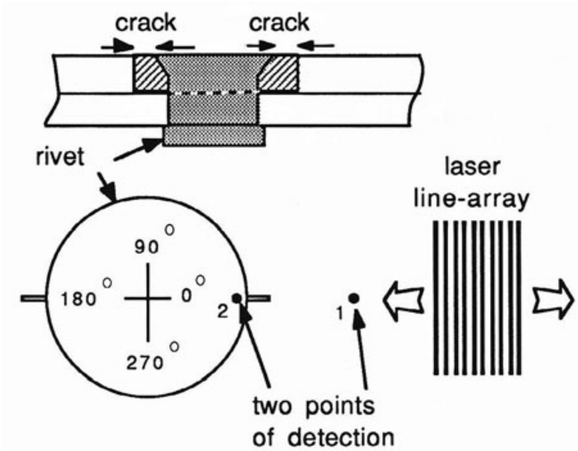

Fig. 4 Schematic of the simulated fuselage panel with cracked rivet holes.

APPLICATION TO NDE OF CRACKS

The narrow-band signal generated using the above technique is applied to the detection of cracks(EDM notches) emanating from rivet holes in a simulated fuselage panel. The panel consists of two aluminum alloy plates riveted together. To simulate cracks, a couple of EDM notches 0.1mm wide and 1.5mm long are made to emanate from the rivet in the top plate as shown in fig. 4.

A tone-burst signal is generated by the laser line-array about 2cm away from the rivet. A dual-probe heterodyne interferometer[1] is employed to detect the wave at two points along its propagation path towards the rivet. As shown in the figure, one probe is positioned off and the other probe is on the rivet in order to pick up the wave before and after propagating into the rivet. A circumferential scanning of the rivet is performed by rotating the specimen such that the generated waves impinge along different radial directions on the rivet. For clarity, we define the 0^o orientation of the specimen as that position where the two probe points are collinear with the rivet crack, see fig. 4. Clearly, for the 0^o and 180^o orientations, we expect that the second probe signal will be substantially attenuated due to the shielding effect of the crack. At other orientations, this attenuation should be much less significant.

Figures 5(a) and (b) show the output of the dual-probe interferometer obtained along directions with and without the presence of a crack, respectively. For the 240^o orientation, where the second probe signal is not shielded by the crack, two tone-burst signals can be discerned from fig. 5(b). However, for the 0^o orientation, fig. 5(a) shows that the second tone burst is significantly attenuated due to crack shielding. This is better brought out by considering the frequency domain signal rather than the time domain signals. Thus, from each trace the two probe signals are windowed out and their Fourier transforms are obtained separately. The resulting amplitude spectra shown in figs. 5(c) and (d) clearly indicate the presence and absence of a crack, respectively. As expected, the fundamental peaks of the narrow-band signals in these spectra are substantially above the noise floor, with consequent improvement in the signal-to-noise ratio of the system.

The data obtained from scanning along different directions were windowed and transformed in a similar manner. A transmission coefficient in direction θ is defined as $T(\theta)=A_2(\theta)/A_1(\theta)$, where $A_1(\theta)$ and $A_2(\theta)$ are the amplitudes of the fundamental peaks corresponding to the first and the second tone-burst probe signals. For convenience of presentation, a normalized transmission coefficient is defined as

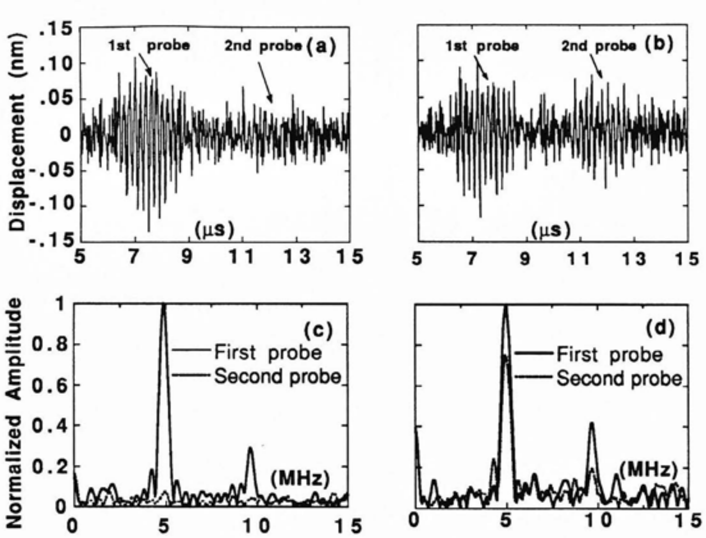

Fig. 5 Tone-burst signals (a) at 0^{o} direction(with crack) and (b) at 240^{o} direction(without crack), and the spectra of the signals (c) at 0^{o} direction and (d) at 240^{o} direction.

$$\mathcal{T}(\theta) = \frac{logT(\theta)\text{-}logT_{min}}{logT_{max}\text{-}logT_{min}} \tag{8}$$

where T_{min} and T_{max} are the minimum and maximum transmission coefficients with respect to the orientation angle θ. A polar plot of $\mathcal{T}(\theta)$ with respect to θ is shown in fig. 6. It is seen that the normalized transmission coefficient goes to zero at 0^{o} and 180^{o} directions, showing clearly the presence of a crack in these directions. There are some sidelobes around the zero transmission directions, which are probably due to the interference between the direct incident wave and the wave reflected by the crack. At the orientations where the crack does not shield the second probe, the normalized transmission coefficient is significantly higher. The variation of $\mathcal{T}(\theta)$ in directions without cracks is due to the random variation in the bonding between the rivet and the plate that arises during the manufacturing process, which leads to partial reflection at the rivet-plate interface.

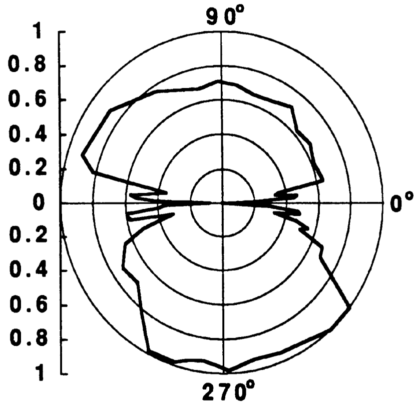

Fig. 6 Normalized transmission coefficient in polar plot.

CONCLUSIONS

In conclusion, it has been shown that narrow-band tone-burst-like surface waves can be generated using laser ultrasonics in the thermoelastic regime. This is achieved by illumination of a laser line-array formed by a simple lens system and an optical diffraction grating. The bandwidth of the surface wave, the fundamental frequency, as well as the efficiency of generation can all be independently controlled by the number, the spacing, and the width of the lines in the laser line-array. The signal-to-noise ratio of the laser ultrasonic generation and detection system in the frequency band of interest can thereby be increased significantly. The narrow-band signal generation and a dual-probe laser interferometer detection have been successfully applied to the detection of cracks on simulated fuselage panels.

ACKNOWLEDGMENT

This work was carried out in the course of research sponsored by the FAA Center for Aviation Systems Reliability, operated by Ames Laboratory, USDOE, for the Federal Aviation Administration under Contract No. W-7405-ENG-82 for work by Iowa State University and Northwestern University.

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